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16. ABSTRACT

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THE NCLAN PROGRAM FOR CROP LOSS ASSESSMENT

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3.1 INTRODUCTION

The Clean Air Act requires the US Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQSs) for "any air pollutant which, if present in the air, may reasonably be anticipated to endanger public health or welfare and whose presence in the air results from numerous or diverse mobile and/or stationary sources" (Padgett and Richmond, 1983). The Agency is responsible for developing and promulgating primary (to protect public health) and secondary (to protect public welfare) NAAQSs. The 1977 amendments to the Clean Air Act require that the criteria (scientific basis) for the standards be periodically reviewed and revised to include new information. In 1978, EPA reviewed the scientific literature to determine the impact of ozone on vegetation and published this analysis in the Air Quality Document for Ozone and Other Photochemical Oxidants (US EPA, 1978). The credibility of the secondary standard for ozone, based in part on these studies, suffered because there were insufficient data to determine reliably either the effects of ozone on the yield of major agronomic crops under field conditions or to determine resultant economic consequences.

Several realities in the late 1970s precluded a credible comprehensive economic assessment.

1. Ozone exposure–response data were not available for the economically important crop species. Relatively few studies measured effects of exposure on growth and yield. In addition, available exposure–response studies were usually not comparable due to important differences in exposure regimes, response variables measured, and exposure methods.

Experimental exposures were often so unrealistic that inferences to the field were inappropriate.
2. Data on the spatial distribution of ozone in agricultural areas were incomplete and not expressed in a form that allowed estimation of potential effects on crops.
3. Important interactions between pollutant exposure and key environmental variables were poorly understood.

On the other hand, advances in experimental exposure technology (Heagle *et al.*, 1973, Lee and Lewis, 1978) and improvements in quality control and data management of EPA's National Aerometric Data Bank (Storage and Retrieval of Aerometric Data (SAROAD) made the time right to generate more realistic exposure–response data and to attempt a comprehensive economic assessment.

In 1980, the EPA initiated a model crop loss assessment program. The effort was launched with a series of meetings with EPA's Office of Air Quality Planning and Standards (OAQPS) and air pollution scientists. Objectives were defined and the merits of alternative methods of achieving these objectives were discussed. The National Crop Loss Assessment Network (NCLAN) was conceived as a multidisciplinary study to produce an economic assessment of the effects of air pollutants on US agriculture based upon state-of-the-science exposure–response data.

NCLAN's primary objectives were to:

1. define the relationships between yields of major agricultural crops and exposure to ozone, sulfur dioxide, nitrogen dioxide, and their mixtures;
2. assess the economic consequences resulting from the exposure of major agricultural crops to ozone, sulfur dioxide, and nitrogen dioxide, and their mixtures; and
3. advance the understanding of the cause and effect relationships that determine crop response to pollutant exposure.

Funding limitations and the resulting priority setting ultimately led to decisions to concentrate field research efforts on developing ozone exposure–response functions (though a few studies using pollutant mixtures were conducted). The process-oriented physiological studies were all but eliminated and the economic assessment was restricted to consider only the effects of ozone. Nevertheless, the NCLAN program approaches the task of developing the "ideal" data set for standard setting on a scale that had never before been attempted.

3.2 RATIONALE FOR THE NCLAN APPROACH TO ECONOMIC ASSESSMENT

Presumably, air pollution exposure imposes costs on production of a given yield. If the costs of producing a given yield under known oxidant exposure are available, a cost function may be estimated econometrically, which defines the

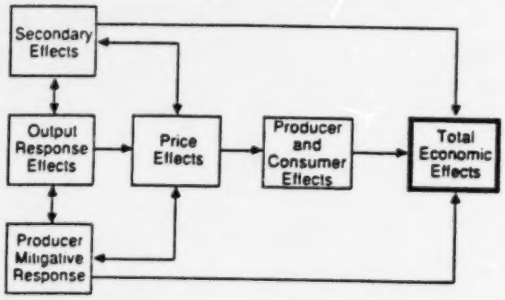

Fig. 3.1. Flow chart illustrating the components of a national economic assessment.

relationship between oxidant exposure and the components of production cost (Mjelde *et al.*, 1984). No explicit crop exposure–response information is required, since this is embedded in the farmers' actual cost and yield data. Unfortunately, there was no national-level database on farm costs that was sufficiently detailed to implement such an analysis. Therefore, other approaches were considered.

These approaches required a knowledge of the biological (yield) response of crops to pollutant exposure and an evaluation of the economic consequence of that biological response (Fig. 3.1). In evaluating the biological response, the interactive effects of air quality, climate, weather, soil fertility, and agronomic practices needed to be considered. In evaluating the economic consequence of the response, allowances had to be made for actions that producers take to mitigate or avoid the effects of air pollution on their crop and for the impact that changes in quantity have had on product price.

The assessment problem was truly interdisciplinary, involving the physical sciences, biological sciences, and economics. The needs of the economic assessment defined the biological information required, and the needs of the biological assessment defined the physical and agronomic information needed. The problem framework had to be structured to ensure that all information-gathering activities were appropriate to the scale of the economic assessment.

3.2.1 Econometric and mathematical programming approaches

Econometric-simulation and mathematical programming approaches appeared to be the most consistent with the conceptual framework for addressing large-scale agricultural assessment problems. Both approaches, in general, build upon crop yield air pollution response functions. Econometric techniques generally begin with multivariate analysis of survey data to define a production function relating the yield of an agricultural crop in a region to variables affecting yield (including air quality). These statistically based yield relationships then become one component of the overall econometric model. Manipulation of the yield relationships can serve to simulate the economic effects of air pollution by tracing their consequences through other relation-

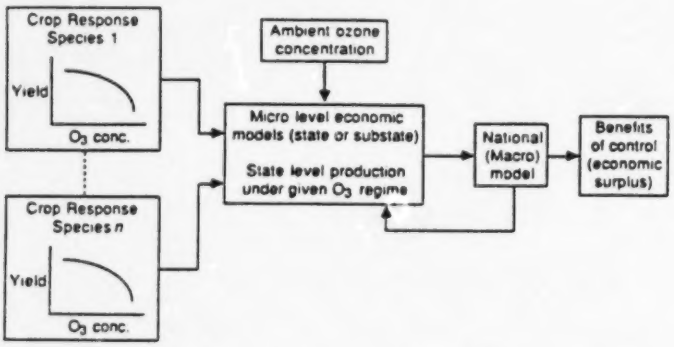

Fig. 3.2. Information flow and logic structure of NCLAN's national economic assessments.

ships in the model. This approach was not adopted because of concerns that the accuracy and resolution of national-level databases on environmental variables were inadequate to separate the relatively small (5–15%) anticipated ozone effect from the effects of other environmental variables on yield. Also, the detection of an ozone effect on yield depends upon a gradient of exposure over the areas sampled. There was concern that the ozone gradient was not steep enough over the major crop growing areas of the United States to permit reliable detection of ozone-related effects.

Mathematical programming techniques appeared to be the most suitable for the assessment problem. In this approach, normative optimization models integrating crop exposure–response data are used to estimate the impacts of varying input parameters, such as air quality, on economic response of the agricultural system. The flow of logic and data requirements of NCLAN economic assessments are illustrated in Fig. 3.2.

3.2.2 Approaches for estimating crop loss functions

Several approaches could be used to estimate crop loss functions. All have their strengths and limitations. Three primary approaches were considered.

The first approach utilizes multivariate statistical techniques to estimate the production function from a regression of spatial yield data on variables suspected to affect yield. Independent variables would have to be randomly sampled in space over a gradient of conditions in the region of interest. Oshima *et al.* (1976) developed response functions for alfalfa in California using this method. It has also been successfully applied to evaluating pest and disease effects on crop yield (James and Teng, 1979). It was successful because the impact of pests or disease was substantial and localized within areas having relatively similar environment and agricultural practices. However, the approach was not considered viable for the NCLAN assessments. Air pollution impacts on crops can be subtle and may be modified as environmental variables change over large crop growing regions. Consequently, a dense sampling pattern over wide geographic areas would be necessary to detect the

5 to 15% yield loss that appears to be typical of many experimental chronic pollutant exposures. In addition, it was considered unlikely that the steep ozone gradient available to Oshima *et al.* (1976) was present in the major crop growing areas of the Midwest. This would make it difficult to distinguish ozone effects from those of other environmental variables.

The second approach utilizes crop simulation models to estimate the response of crops to important inputs (including air pollution). Using available crop simulation models as a starting point, effects of pollutant exposure on yield are modeled to conform to results of laboratory and field experiments. Behavior of the models is then validated against independent experimental field data generated over the range of conditions for which extrapolation is desired. The models are then exercised with available regional input data to generate regional estimates of yield loss. The economic consequences of these loss estimates can then be evaluated.

The strength of this approach was that the process of constructing the models and generating the appropriate data to run them leads to greater understanding of the underlying mechanisms causing the observed yield responses. Such understanding adds credibility to the assessment and aids in setting reasonable limits on extrapolation of results.

However, there were also serious limitations to this approach. Most crop growth models available at the time had high temporal resolution (hourly time step) but were spatially lumped (representing growth effects on a small plot or plant basis). Therefore, to estimate yield effects for an entire crop growing region, the models would have had to be run under a large variety of ozone-environment regimes from a random sample of locations within the region. Such data, with sufficient temporal resolution, for driving variables were generally not available and would be prohibitively expensive to gather. Also, the costs and lead time required to develop and validate the crop models made this approach infeasible as the primary method for producing the exposure–response functions in NCLAN. However, simulation modeling has played a crucial secondary role in modeling the effects of water stress on plant response to ozone and applying this interaction to the economic model (e.g., King, 1987; King and Nelson, 1987).

The third approach utilizes carefully designed and standardized field experiments to generate representative exposure–response functions for major crop species. With adequate replication of field experiments in time and space, empirically based exposure–response functions can be generated that are representative of the crop growing region. The advantages of this approach are that, in the semi-controlled field exposures, yield effects could be definitely associated with pollutant exposure, yield response could be ascertained for exposures at and above ambient conditions (useful for evaluating the consequences of alternative regulatory scenarios in assessments), and the accuracy and precision of the individual response functions can be controlled (through experimental design) and quantified. However, these field experiments are expensive and require a full field season to generate a single replicate of an exposure–response function. Because a large number of these functions are

required to provide adequate spatial and temporal replication, this approach suffers some of the same limitations of the first two. Nevertheless, NCLAN scientists, peer reviewers, and the OAQPS staff agreed that, considering the pros and cons of the options available, this approach would provide the most useful information within time and budget constraints.

3.3 THE NCLAN APPROACH

The field experimental approach was chosen as the primary method for generating exposure–response information. Physiological studies and mechanistic simulation modeling were used to provide supplementary information useful in interpreting and extrapolating the empirically generated functions.

A series of nationally coordinated field studies was conducted to provide crop exposure–response data representative of the areas in which they were conducted. A network of field sites was established in regions where ten field crops (corn, soybeans, wheat, hay, tobacco, sorghum, cotton, barley, peanuts and dry beans), accounting for roughly 85% of US acreage, are planted (Fig. 3.3). Ozone exposure–response experiments were conducted for each. When funding permitted, additional independent variables were included in the field experiments (e.g., water stress or other pollutants). Physiological measurements were taken during the growing season when possible, to aid in interpreting results and modeling interactions of independent variables. Response functions so generated and interpreted were used in an economic assessment of the consequences of ozone exposure to US field crops.

Fig. 3.3. The National Crop Loss Assessment Network, Regional Boundaries and Location of the Regional Crop Loss Assessment Projects (RCLAP). Box = auxiliary field site, solid circle = administrative center and field site.

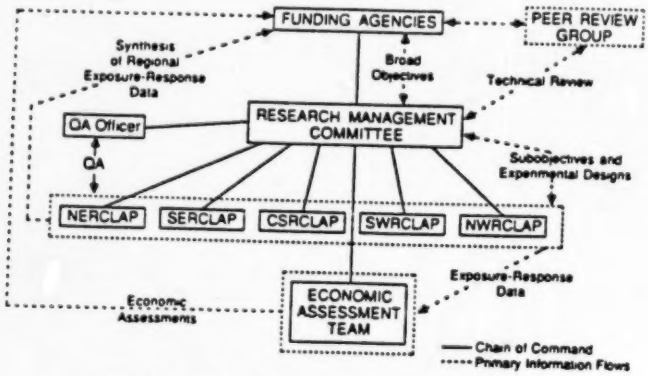

Fig. 3.4. NCLAN organisation and management.

The interdisciplinary nature and widely dispersed locations of NCLAN research made carefully coordinated action and regular, effective communication prerequisites for success. A participatory management structure was implemented to facilitate these goals (Fig. 3.4). The principal investigators from participating research institutions and the EPA program manager constituted a governing Research Management Committee (RMC). The RMC was broadly responsible for translating articulated Agency needs into appropriate research activities within budget constraints. The RMC provided a forum for program planning, tracking, and problem resolution. The RMC was the primary focus for interproject coordination and was primarily responsible for ensuring the comparability of methods used in field research.

Field research was undertaken within the five Regional Crop Loss Assessment Projects (RCLAPs). The regional projects were responsible for research conducted within their region and were accountable for the resources assigned to those projects, following guidelines approved by the RMC.

NCLAN research was quality controlled through two independent processes. An interdisciplinary peer review group from outside NCLAN reviewed research progress annually and recommended project improvements, terminations, or changes in direction. Approximately 50% of the peer review group was replaced every 2 years. This allowed reasonable continuity and infusion of new ideas, but prevented the gradual development of conflicts of interest that might prejudice the group's objectivity. Secondly, the process of generating and analysing research data was subjected to a strict quality assurance program (Coffey *et al.*, 1988). Each research project was subjected to an annual quality assurance audit to ensure that data were of known quality, accuracy, precision, and completeness and were being generated with approved protocols. Audits often detected operational problems before they became serious and prevented loss of data.

3.4 NCLAN ACCOMPLISHMENTS

In its 8-year history, NCLAN has maintained a remarkable record of accomplishing what it set out to do on time and within budget. The majority of the program's funding and research efforts have been devoted to developing crop exposure–response functions of known and documented quality using generally comparable experimental protocols. Exposure–response functions have been developed for the original target agricultural species (see Table 3.1 for selected examples). For many species, the response functions were derived from experiments replicated in at least two growing seasons on more than one cultivar. In some cases, where the crop is normally grown in a large area with wide variability in environmental conditions (e.g., soybeans and wheat), experiments were conducted at more than one site. The exposure–response data set is by far the most comprehensive available for ozone effects on vegetation. The electronically stored database is available to the scientific community for further analysis and scrutiny from the US Environmental Protection Agency, Corvallis, OR.

A second significant accomplishment is the completion of economic assessments fully utilizing the NCLAN exposure–response database. This required conversion of SAROAD air-quality data into an appropriate form and development of an appropriate model of the national farm economy. NCLAN pioneered the use of kriging (a statistical spatial interpolation methodology) to estimate ambient ozone exposures from point sample data in the SAROAD database (Lefohn *et al.*, 1987*b*). The economic model developed for NCLAN by Adams *et al.* (1984) was the most comprehensive and sophisticated of any used to date in air pollution assessments.

In 1984, a preliminary assessment was completed (Adams *et al.*, 1984) utilizing exposure–response functions available at that time for six of the major

TABLE 3.1
Examples of exposure–response functions developed by the NCLAN program*

Species "cultivar"	*Weibull parameter estimates*			*Relative losses at three 7-h/seasonal means (ppm)*		
	$\hat{\alpha}$	$\hat{\sigma}$	$\hat{c}$	0·04	0·05	0·06
Barley "Poco"	1·988	0·205	4·278	0·1	0·2	0·5
Bean, kidney	2878	0·12	1·171	11·0	18·1	24·8
Corn "Pioneer 3780"	12533	0·155	3·091	1·2	2·6	4·8
Cotton "Acala SJ-2"	5546	0·199	1·228	5·9	10·0	14·0
Peanut "NC-6"	7485	0·111	2·249	6·4	12·3	19·4
Sorghum "Dekalb-28"	8137	0·296	2·217	0·8	1·5	2·5
Soybean "Corsoy"	2785	0·133	1·952	5·6	10·4	15·9
Wheat "Roland"	5479	0·113	1·633	9·4	16·4	23·7

* The Weibull parameters and estimated relative yield loss data are from Heck *et al.*, 1984.

agricultural crops (corn, soybean, wheat, cotton, sorghum and barley) that account for approximately 70% of the total acreage of US field crops. This assessment estimated that reductions in ambient ozone concentrations of 10, 25 and 40% would yield annual economic surpluses of 0·67, 1·71 and 2·52 billion 1980 dollars, respectively. The final assessment (Adams *et al.*, 1988) is significantly more expensive.

Finally, NCLAN Program participants demonstrated that a long-term coordinated, multidisciplinary air pollution study is possible. The successful partnership of EPA, academia and other agencies was facilitated by a well-considered management structure, but it was the dedication, patience and personal motivation of principal investigators that ensured the program's viability and ultimate success in achieving overall goals.

3.5 IMPLICATIONS FOR FUTURE RESEARCH

Future research needs can be assessed from several perspectives. We have structured our recommendations upon three primary end uses of crop effects data: (1) economic assessment studies, (2) development of ambient air-quality standards, and (3) advancement of scientific understanding of pollutant effects on vegetation. We recognize that each of these uses may require different kinds and amounts (intensity) of research effort. We have attempted to be objective in developing these recommendations, but are unapologetic for any biases that remain.

3.5.1 Economic assessment

A substantial amount of exposure-response data has been collected (Heck *et al.*, 1983, 1984) to support an economic assessment of ozone effects on agriculture (Adams *et al.*, 1984, 1988). The results of NCLAN economic assessments clearly show that ozone has a significant impact on the agricultural economy. It is now appropriate to ask, how much improvement in the accuracy and precision of these estimates is justified in support of standard setting, and what additional data are needed to provide this improvement?

3.5.1.1 Do we need more and better national-level assessments?

The initial economic assessment (Adams *et al.*, 1984) was based on the six crop species that are grown on approximately 70% of the crop acreage in the U.S. The final economic estimate (Adams *et al.*, 1988) will be based on eight crops representing approximately 90% of the total US crop acreage. The addition of more crop species is unlikely to greatly influence the magnitude of economic benefit estimates in future national-level assessments.

As a part of the preliminary economic assessment, Adams *et al.* (1984) conducted a series of sensitivity analyses to estimate the influence of various factors such as cultivar selection (differential cultivar sensitivity), ambient ozone concentration, and soil moisture status on the economic assessment. Individually, these factors did influence the magnitude of the monetary losses

up to approximately 70%. However, several of the sources of error introduced by uncertainty in the crop less estimates tended to cancel each other out. It is not clear that additional accuracy in the crop loss functions would significantly improve the precision of future economic assessments.

Empirical studies of Adams *et al.* (1982) show that the quality of the economic and biological response information contributes equally to the reliability of the final economic assessment. Consequently, improvements in economic estimates will require not only improvements in the representativeness and precision of the ozone/crop loss functions but also characterization of the economic processes on which the assessment is based.

Finally, there are sources of uncertainty associated with the estimation of the ambient ozone concentrations as well as with the economic model and with the crop-response data. A continued reduction in uncertainty in only one of these areas will not necessarily increase the credibility of the resulting national economic assessment.

3.5.1.2 Regional crop loss assessments: many unanswered questions

Regional crop loss assessments, on the other hand, could be improved substantially by more accurate and more complete crop loss data. The NCLAN crop species were selected to represent the major fraction of US agriculture with the minimum number of field experiments. The crop/cultivar selection did not reflect the range and diversity of crops grown in all regions of the country.

These data deficiencies can significantly influence the results of regional crop loss assessments. For example, a recent EPA study that attempted to use data from the NCLAN program for assessing the impacts of ozone on agriculture in the Northeast found that the species for which NCLAN had developed exposure–response functions accounted for less than 50% of the agricultural value of the area. Clearly, in this case, data on additional crops are needed to reduce the errors in the regional economic assessment.

We suggest that future economic assessments focus on specific crop-growing regions. By limiting the scope of such studies to a specific region, additional effort can be placed upon improving the resolution of ambient ozone exposure data, utilizing region-specific experimental exposure regimes, and testing the crop species/cultivars relevant to the region.

Ecoregions (e.g., Omernik, 1987) identify discrete areas of the country that are relatively homogeneous in climatic and edaphic factors. Ambient ozone and environmental data typical of these ecoregions could be used as treatment levels in studies to determine the variation in plant response to ozone within and among ecoregions and to identify the key factors that cause or control the variation. These improvements in data specificity should improve resulting economic assessments.

3.5.1.3 So many cultivars, so little time

Commercial cultivars continue to be introduced that have not been and cannot be studied as extensively as those studied in the NCLAN program. It will never be possible to study all regionally important crops or crop cultivars

or to account for the ever-changing mix of cultivars. Consequently, methods are needed for rapidly screening cultivar response to ozone and for making inferences about the ozone response of untested species or cultivars from the response of tested species or cultivars.

3.5.1.4 Alternative approaches to economic assessments should be tested

Most previous economic assessments have been based on exposure–response functions (Adams *et al.*, 1984; Kopp *et al.*, 1985; Shortle *et al.*, 1986). However, the use of alternative methods with different inherent assumptions would provide a good check on the results of exposure–response-based assessments. Mjelde *et al.* (1984) used the duality approach to assess the impacts of ozone on grain production in Illinois. Their estimates of the monetary impact were similar to those estimated using the exposure–response function approach. In this case, the duality method was an inexpensive means of producing economic benefit estimates that were consistent with those produced using crop-response functions. However, to date, the duality approach has not been applied on a regional or national basis.

3.5.2 Ambient air-quality standards

Answers to several questions are needed to support standard setting. Relevant questions include:

1. What is an adverse effect?
2. At what levels of pollution do adverse effects occur?
3. What is the magnitude of variation in adverse effects among species and plant cultivars?
4. What is the appropriate air-quality measure (e.g., averaging the time of the exposure that relates plant response to ambient ozone concentrations)?

To provide the necessary scientific facts to answer these and related questions, data from an array of scientific studies are needed.

3.5.2.1 What aspect of pollutant exposure causes the problem?

The temporal dynamics of pollutant exposure are thought to influence plant response. The relative influence of the components of exposure dynamics (exposure concentrations, durations, frequencies, and respite intervals) on plant response is not well understood. Several lines of evidence suggest that peak pollutant concentrations have a greater role in determining plant response than long term average concentrations (US EPA, 1986).

Various air-quality summary statistics have been used to characterize pollutant exposure. The difficulty in selecting the most appropriate air-quality measure has been summarized by Heagle and Heck (1980). Ambient and experimental ozone exposures have been presented as seasonal, monthly, weekly, or daily means; peak hour means; number of hours above a selected concentration; or the numbers of hours above selected concentration intervals. However, none of these statistics adequately characterizes the relationships

among ozone concentration, exposure duration, interval between exposures (respite), and plant response. A recent analysis illustrated that no one measure was best for all crop species analysed (Lee *et al.*, 1988). However, measures of air quality that emphasized the importance of peaks and accumulated the impacts of the exposure over the season performed better than other measures of exposure.

3.5.2.2 How reliable are the NCLAN crop response functions?

NCLAN was designed, within the necessary time and financial constraints, to provide national assessments of agricultural crop losses likely to occur from ozone exposure. The experimental design was formulated to address the major sources of variation that were originally thought to have the greatest influence on ozone-induced crop losses. Within the Program's resource constraints, it was not possible to determine the representativeness of the NCLAN exposure–response functions. To lend credibility to the NCLAN exposure–response data and the resultant economic assessment, the reproducibility (over time and space) of the exposure–response functions must be established.

Several experimental approaches could be used to validate the exposure–response functions. For example, open-top chamber studies could be conducted at one or more field locations, using a range of simulated ambient ozone exposure regimes (that mimic the temporal variations, as well as concentration ranges in ambient air). Thus, the growing environment would be the only uncontrolled variable. Because simulated ambient exposure can be replicated from year to year and across sites, the only uncontrolled source of variation is that attributable to environmental conditions. Although this research will do little to reduce possible sources of error in the response functions, it will at least permit an estimate of the possible errors that result from varying environmental conditions.

Consideration should also be given to using chemical protectants to validate the exposure–response functions over a range of conditions. Initial studies should be conducted in open-top chambers to determine if the chemical protectant has a direct effect on the crop in the absence of ozone. Subsequent studies should be conducted using open-top chambers at one location and studies with chemical protectants at several locations in the geographic region of interest. The results from the chemical protectant studies would be compared with those predicted from open-top chamber studies as a means for validating the response functions and determining possible biases associated with either method.

3.5.2.3 Are interactions between pollutants important?

The study of the effects of pollutant combinations on plants is based on the premise that pollutants co-occur in the atmosphere and that together they may induce more (or less) injury than that induced by the additive effects of the individual pollutants. Components of ambient air, such as sulfur dioxide or nitrogen dioxide may moderate or change plant response to ozone (e.g., Ormrod, 1982). The magnitude of the potential modifications varies with plant

species, cultivar, pollutant concentration, duration and frequency of exposure, and the environmental and edaphic conditions in which plants are grown.

However, as future studies of pollutant combinations are planned, greater consideration must be given to the pollutant exposure regimes. The regimes should reflect the concentrations and frequency of pollutant occurrence typical of the area of study or for which inferences will be made. It is not sufficient to simply assume that the gases must co-exist in the atmosphere because they are emitted into the atmosphere.

This simplistic approach fails to account for the temporal and spatial variation in pollutants and their levels of occurrence. Co-occurrence of sulfur dioxide, nitrogen dioxide, and ozone at phytotoxic levels is relatively rare (Lefohn and Tingey, 1984; Lefohn *et al.*, 1987*a*). Also, though most previous studies of plant effects have considered only the simultaneous occurrence of pollutants, most co-occurrences are sequential rather than simultaneous. Because ozone does not frequently co-occur with sulfur dioxide and nitrogen dioxide, greater consideration should be given to studying the interaction of ozone with other regionally distributed pollutants such as acidic precipitation and acidic fog.

In future studies, consideration should also be given to simulating the temporal patterns of pollutant occurrence. In ambient air, nitrogen dioxide concentrations frequently peak and then decline due to photolysis preceding the elevated levels of ozone. Runeckles and Palmer (1987) exposed plants sequentially to nitrogen dioxide and then ozone. Nitrogen dioxide pretreatment altered the plants' subsequent response to ozone.

3.5.2.4 How do environmental variables influence ozone response?

It is well established that environmental factors such as light, air temperature, relative humidity, and soil moisture significantly affect the response(s) of plants to ozone and other air pollutants (e.g., US EPA, 1986). Because these factors vary greatly both temporally and spatially, their effects on ozone-induced yield loss in crops require better explanation. A greater understanding of the effects of environmental factors, such as relative humidity, on ozone-induced injury or yield loss is also important for establishing a process-based, theoretical approach for predicting such injury or crop impacts across different locations and years.

The multitude of factors (environmental, nutritional, edaphic, etc.) and subsequent interactions that may influence plant response to ozone are too numerous to analyse effectively and study individually in a reasonable period of time. Consequently, we must consider alternative approaches to the sequential study of the individual factors.

For example, it may be possible to rank the importance of the various factors based on our knowledge of their physiological and biochemical influences on plants. Their relative importance in altering the ozone impact could then be inferred. Alternatively, principal components analysis (PCA) could be applied to experimental data to determine which combination of factors is most important in altering the plant response. Once the "short" list

of important factors is known for a particular regional environment, future studies could elucidate their interrelationships.

3.5.3 Advancement of scientific understanding

Because of limitations in funding and the need to provide the essential data for the economic assessment, much of the NCLAN research has been limited to an empirical approach. This technique provided large amounts of plant response data but contributed relatively little to understanding the mechanisms responsible for plant response. To ultimately understand how ozone impairs plant growth and yield and to use this knowledge in a predictive mode, an improvement in our understanding of the basic mechanisms of ozone phytotoxicity is needed.

Although there have been numerous biochemical and physiological studies to investigate the fundamental nature of ozone phytotoxicity, most have been limited in scope and have focused on a single level of study. For example, the majority of studies of biochemical and/or cellular processes have not considered ozone uptake. Consequently, we frequently know that different clones or cultivars exhibit different biochemical responses to ozone, but we do not know if these differences are the result of different amounts of ozone flux into the plant or if the differences actually represent different biochemical sensitivities to ozone. Unless there is more integration and coordination among the various studies, this limitation will persist.

Future studies should be initiated to develop a conceptual framework of how ozone affects plant processes. From a comprehensive conceptual framework, the data and information necessary to advance scientific understanding could be identified. Given the numerous processes that could be investigated, a conceptual road map is needed to ensure that the limited financial resources are directed toward the most important or promising areas.

An "expert system" may provide a suitable format for a comprehensive conceptual framework. Expert systems are computer programs that suggest solutions to complex problems by mimicking human reasoning processes and employing a knowledge base developed by human experts (Stone *et al.*, 1986). All expert systems contain a data or knowledge base and an executive program that interprets the knowledge base to answer questions posed.

The knowledge base is a collection of facts, generalities, opinions, and empirical information that represents the state of the world, encoded so that the relevant relationships among facts and generalities can be understood. The executive program controls the system's reasoning process. It determines the sequence of logical steps that leads to solution of the problem. Expert systems provide an accessible and powerful means to transfer existing expert knowledge and experience to a non-expert.

The expert system would constitute a dynamic decision-making model depicting our developing understanding of the effects of ozone and other stresses on the quantity and quality of crops and the ramifications of these effects in the agricultural infrastructure. The knowledge base could function as an "electronic air-quality criteria document" that is continually updated. The

executive program could incorporate the necessary scientific reasoning to apply the growing knowledge base to various Agency regulatory problems.

In the process of developing and implementing an expert system, types of data necessary to exercise the system in a problem-solving mode would become clear. Research could then be designed to provide the data efficiently and systematically.

3.6 SUMMARY

In 1980, the US EPA undertook initiation of a crop loss assessment program. The NCLAN was conceived as a multidisciplinary study to produce an economic assessment of the effects of air pollutants on US agriculture based upon state-of-the-science exposure–response data. A network of field sites was established in regions where ten field crops accounting for roughly 85% of US acreage are planted. Replicated ozone exposure–response experiments were conducted for each of the crops. The resulting exposure–response data set is by far the most comprehensive data set for ozone effects on vegetation available.

National economic assessments have been completed fully utilizing the NCLAN exposure–response database. This required conversion of SAROAD air-quality data into an appropriate form and development of an appropriate model of the national farm economy. NCLAN pioneered the use of kriging to estimate ambient ozone exposures from point sample data in the SAROAD database (Lefohn *et al.*, 1987*b*). The farm economy model developed by Adams *et al.* (1984) was the most comprehensive and sophisticated of any air pollution assessment to date.

A preliminary assessment (Adams *et al.*, 1984) in 1984 estimated that reductions in ambient ozone concentrations of 10, 25 and 40% would yield annual economic surpluses of 0·67, 1·71, and 2·52 billion 1980 dollars, respectively. The results of the final assessment (Adams *et al.*, 1988) significantly improve these estimates.

Several sources of uncertainty in the estimates of economic loss remain that point out future research directions. Given that ozone has an economic impact on agriculture, it is appropriate to ask, how much improvement in the accuracy and precision of these estimates is justified in support of standard setting and what additional data are needed to provide this improvement?

We conclude that significantly improving the national economic assessments will be costly. There are many independent areas of uncertainty in the analyses, and a continued reduction in uncertainty in one or a few of these areas will not necessarily increase the credibility of the resulting national economic assessment.

We suggest that future economic assessments focus on specific crop growing regions. Exposure–response data are needed for important crops in several regions of the United States. By limiting the scope of such studies to a specific region, additional effort can be placed upon improving the resolution of

ambient ozone exposure data, utilizing region-specific experimental exposure regimes, and testing the crop species/cultivars relevant to the region.

Methods are needed for rapidly determining the ozone response and for making inferences from the response of tested species or cultivars about the response of untested species or cultivars. In addition, alternative approaches to economic assessments should be tested.

Research has not yet determined unambiguously the relative importance of the components of pollutant exposure in inducing plant response. Both field and controlled-environment studies are needed to determine the relationships between crop response and the statistics used to characterize ozone exposure.

Research is also needed to determine the reliability of the NCLAN exposure–response functions and to determine how important interactions with other pollutants and other environmental variables are in determining plant response to ozone exposure.

Future research could be conducted more efficiently if a general conceptual framework relating pollutant exposure to plant response were available. From such a conceptual framework, it would be possible to identify the data and information necessary to advance scientific understanding. Given the numerous processes that could be investigated, a road map is needed to ensure that the limited financial resources are directed toward the most important areas.

An expert system might provide a useful format for the conceptual framework. Expert systems are computer programs that suggest solutions to complex problems by mimicking human reasoning processes and employing a knowledge base developed by human experts (Stone *et al.*, 1986). All expert systems contain a data or knowledge base and an executive program specifying rules for use of the knowledge base.

The process of developing and implementing an expert system would make evident the types of data necessary to exercise the system in problem solving. Research could then be designed to efficiently and systematically provide those data.

The expert system would also provide a means to continually incorporate improved scientific understanding into regulatory decision-making. The knowledge base could function as an "electronic air-quality criteria document" that is continually updated and the executive program could incorporate the necessary scientific reasoning to apply the growing knowledge bases to suggest solutions to various Agency control scenarios.

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